Reviewer 1 Comments (27th August 2025)

Review of "Land subsidence dynamics and their interplay with spatial and temporal land-use transitions in the Douala coastland, Cameroon."

General comments:

The paper presents original research on land subsidence in a rapidly growing coastal region. This work is important as the paper notes, because "there have been no specific studies on land subsidence mechanisms for the coast of Cameroon, leaving it uncharted". The paper is generally well written. I am particularly interested by the analysis of how subsidence rates change following urbanization. However, I have concerns about how the InSAR analysis was performed, especially considering that it is the primary source of data supporting the authors' analysis and conclusions. The section describing the InSAR analysis is severely lacking detail and contains a number of erroneous statements. This casts doubt over the entire subsequent analysis and conclusion. In addition, I have some suggestions for how the data are presented, because they are not easily interpreted in their current form.

Specific comments (major):

1. No time series analysis or accompanying coherence matrices were provided in the either the article or the supplementary material. I find this rather problematic, as the entire premise of the paper revolves around analysing that data correctly. Particularly with regard to the non-urban to urban transition zones, it is very likely that no coherent interferometric combinations exist for these pixels which cross the transition to urban. The authors should show the coherence matrix for such a region. It is probable that two separate subsidence rates would need to be estimated, one preceding urbanization and one after.

Response: We thank the reviewer for their comment. To clarify, our study does not analyse simultaneous land-use change and land-subsidence dynamics. Instead, we investigated the correlation between past (1992–2015) to recent (2017–2022) land-use transitions and the contemporary subsidence rates observed during 2018–2023. Our hypothesis is that current subsidence rates and patterns can be related, at least partially, to antecedent land-use changes. As summarized in Table 6, all but one of the transition paths are built-up areas after 2017, confirming that the pixels included in the analysis correspond to coherent scatterers throughout the monitoring period. To further strengthen our study, we have added displacement time series for all land-use change classes listed in Table 6 (see supplementary Figs. S5). In addition, a mean coherence map and representative coherence time series for interferometric pairs from urban, peri-urban, and discarded pixels are now provided in Supplementary Figures S4A and S4B.

2. Lines 138--139: "To improve the signal-to-noise ratio of the interferometric phase, a multi-looking factor was used to create a pixel dimension of approximately 75 m in the range and azimuth directions". A 75x75 m2 multilooking is approximately 55 pixels, which for S1 IW mode means approx. 35 looks/independent samples. Why was this number chosen? For DS regions 35 looks is likely insufficient to suppress noise, and for PS regions a 75x75m2 pixel is far too large for such a mixed environment.

Response: We thank the reviewer for raising this important point. The choice of ~75 m ground pixel spacing results from a multilooking factor of 32 (range) by 6 (azimuth), providing approximately 192 independent looks. This spatial averaging is widely employed in regional and localized InSAR studies utilizing Sentinel-1 IW time-series, with similar or larger pixel sizes used in comparable urban subsidence studies (e.g., Cigna & Tapete, 2021: Mexico City, ~75 m; Ohenhen et al., 2023: US East Coast, ~50 m; European Ground Motion Service, ~100 m; Payne et al., 2025: Iran, ~100 m). Additionally, we note that >80% of the InSAR pixels in our study fall within built-up environments during the 2018–2023 observation period, indicating that our study area is predominantly urbanised and characterised rather than a mixed environment (note the transition pixels discussed above). The 75 m resolution provides an appropriate balance between noise suppression and spatial detail for capturing subsidence patterns in this urban-dominated setting, while maintaining sufficient coherence for reliable time-series analysis. A summary of this reasoning has been added in the revised ms (lines 141-144)

3. Lines 143--145: "To this end, the so-called noisy pixels with coherence less than 0.65 (for distributed scatterers) and amplitude dispersion more than 0.3 (for permanent scatterers) were discarded following Lee and Shirzaei (2023)."

a) Coherence is a time-varying quantity and depends on the combination of images used to form an interferogram. The text seems to imply that each pixel can be assigned a single static value of coherence. How was this implemented? And if it is per interferogram, how do you ensure a continuous time series of coherent phases?

b) 0.65 is a very high threshold for DS pixels in agricultural or urbanizing regions. I find it hard to believe that more than only a few pixels would pass this threshold spanning the entire archive of imagery used in this study.

c) The article makes no mention of a pixel-based PS algorithm being used, however the use of amplitude dispersion as a quality metric seems to imply a PS methodology. What is actually being done with these pixels? If a PS algorithm is used in combination with the DS, how are the two analyses integrated?

Response: We thank the reviewer for their comment. We have revised the Methods section (Lines 139–156) to clarify that our analysis implemented a SBAS-type framework following Lee and Shirzaei [2023], which applies a statistical procedure to identify and retain only stable pixels. In this framework, permanent scatterers (PS) were identified using an amplitude dispersion index <0.3, while distributed scatterers (DS) were evaluated using temporal mean coherence across the interferogram stack. DS pixels with

average coherence >0.65 and low coherence variance were retained and assigned to Voronoi cells around adjacent PS pixels. A Fisher's F-test then evaluated amplitude similarity between DS and PS within each cell. DS pixels passing this statistical test were reclassified as stable distributed scatterers, ensuring the final dataset comprised only reliable scatterers for time-series analysis (see Lee and Shirzaei, 2023 for additional details). Supplementary Figures S4A and S4B provide coherence maps and time series demonstrating the temporal stability of our selected pixels.

4. Lines 147--148: "A 2D phase-unwrapping algorithm was used to examine the complex interferometric phase noises and identify elite pixels (i.e., pixels with an average coherence greater than 0.7) (Shirzaei, 2013)." This is a very problematic statement. PU algorithms attempt to estimate relative ambiguity levels in adjacent pixels by applying spatial continuity constraints. They do not "examine noise". The description provided in the reference is about low-pass filtering interferograms based on the values of some identified high-quality pixels (called "elite pixels"). This is not a standard approach, and the authors risk removing high frequency parts of the signal of interest by doing so. This is likely only going to be effective at finding slowly varying, deep-seated subsidence drivers, which is not the focus of this paper. I recommend that the authors discard this method in favour of approaches accepted by the community in general such as SqueeSAR (Ferretti 2011) or similar. If the authors insist on this method, they must at least provide strong justification for doing so.

Response: We thank the reviewer for this comment and for pointing out the need for clarification. We agree that our original description was misleading. In the revised manuscript (Lines 158–160), we now state: *"A 2D minimum cost flow phase unwrapping algorithm was applied to estimate absolute phase changes in each interferogram, using a sparse set of elite pixels selected as described above (Costantini, 1998; Costantini & Rosen, 1999)."* Thus, we do not use phase unwrapping to "examine noise," but rather to unwrap interferometric phases on a network constrained by statistically selected elite pixels. The WabInSAR algorithm employed in this study has been validated in multiple studies for producing spatially continuous deformation time series in both urban and peri-urban settings.

5. Line 151--152: "….using a local reference point (longitude: 9.61, latitude: 4.22) located 20 km outside the study area" Why was this point chosen? How was the atmospheric phase correctly removed if the reference point was not part of the analysis?

Response: We thank the reviewer for their comments. We have revised the manuscript (Lines 162–166) to clarify the choice of reference point as a stable point outside the city. The reference point, while outside the urban center, remains within the same SAR scene coverage and experiences the same atmospheric corrections as the study area. The final deformation maps presented in the manuscript were subsequently trimmed using a polygon corresponding to the urban extent of Douala. We now show the location of the reference point in Figure 3.

6. Line 166: "Given $\{LOSA, LOSD\}$ and $\{\sigma A\text{^}2, \sigma D\text{^}2\}$ are the LOS displacement and variances for a given pixel" How are these variances obtained?

Response: We thank the reviewer for their comments. We have revised the manuscript (Lines 162–166) to clarify that the LOS velocity is obtained as the slope of the reweighted least-squares fit to the time series, and the associated variance is derived from the uncertainty of this regression slope.

7. Table 6: The extreme values reported in this table need to be checked. In particular, the cropland and wetland areas are prone to temporal decorrelation and phase unwrapping errors, which often results in overestimated subsidence rates (see Morishita and Hanssen 2015, Tampuu 2022). InSAR analysis often fails in regions like these and the authors need to take the dynamics of the region they are monitoring into account. Again, an analysis of the coherence matrices in these areas would be very beneficial.

Response: We thank the reviewer for their comments. The values reported in Table 6 correspond to the minimum, mean and maximum values of land subsidence in each of the following corresponding land-use change classes. Over the period covered by the InSAR images the areas consistently remained urbanised (see the 2017 and 2022 columns), with no issue in terms of temporal decorrelation. The land-use changes are not referred to the simultaneous changes of land use and land subsidence but correspond to the past and present change of land use within a specific area and how these changes correlate the current observed land subsidence value. Time series data for these changes are equally updated in the supplementary materials (Fig.S5A, B, C and D).

8. Line 370: The discussion on groundwater extraction is lacking. Are we talking about deep or shallow aquifers, and how does the urban data support the conclusion? "The land subsidence rates decreased with an increase in building height, suggesting the potential influence of foundation type on land subsidence" -- that is highly doubtful. More likely, deeply founded buildings are less prone to subsidence caused by draining the phreatic groundwater. i.e. we can't see the subsidence happening on the surface at those locations. This would suggest that the city is not obtaining water from a deep aquifer. Is that the case? Again, the lack of a real PS processing methodology casts doubt over the entire conclusion.

Response: We thank the reviewer for their comments. In the literature, we recalled that groundwater is one the main causes of land subsidence in numerous cities around the world including cities like Jakarta, Shanghai and Mexico. However, our objectives in this study were centred on understanding if a correlation exists between land subsidence measured over the period 2018-2023 and when the coastland was transformed from non-urban to urban zone over the past 3 decades. Also, the type of constructions has been investigated, and we agree with this reviewer about the fact that "deeply founded buildings are less prone to subsidence caused by draining the phreatic groundwater. i.e. we can't see the subsidence happening on the surface at those locations.**". Our original sentence has been rephrased to make clearer this concept. By the way, we agree with a previous reviewer comment that, the possibility to distinguish between the displacement of tall and low buildings would be better captured using a PS-based interferometric processing chain. The InSAR data used here provides first insights and indications, however they carry**

additional uncertainties due to the processing chain which provides a spatial smoothed signal. This limitation of our study has been highlighted in the Discussion (lines 480-466). We recognised the fact that groundwater pumping could be a factor significantly contributing to land subsidence especially because Douala is rapidly growing coastal city where more groundwater is needed for population and industrial needed. Unfortunately, information about groundwater pumping rates, drainage, recharge, and pressure evolution in the shallow and deep aquifer system is very limited in Douala. Therefore, it cannot be addressed in the present analysis. We have highlighted more strongly this important gap in the Discussion. Data completely lack or are not made available from governmental institutions and private companies. This challenge is not limited to the study area but extend to the whole region of sub-Saharan Africa, as recently highlighted by Avornyo et al., 2023 and Ikuemonisan et al., 2023. The need of establishing, using, and maintaining in-situ monitoring networks have been highlighted too (lines 489-477). Remote sensing quantification, e.g., through GRACE, cannot outpace the complete gap occurring nowadays.

9. Regarding the comparisons between LULC classes. The authors should include time series data, in order to demonstrate the differing dynamics of these types of regions, ideally at least one from each of the identified classes.

Response: We thank the reviewer for their comments. We have included the average InSAR time series plots for each land-use changes category as illustrated in the supplementary, Fig. S5. Beyond this, we have also included the land subsidence time series of some selected points in the study areas characterised by different changes as shown in Figure 6.

Specific comments (minor):

1. Why are orbital and topographic phases removed after unwrapping? This should be done beforehand to reduce variability in the phases.

Response: We thank the reviewer for this observation. Our analysis follows the WabInSAR (Wavelet-based InSAR) framework, in which residual orbital ramps, DEM-related errors, and the topography-correlated component of atmospheric delay are corrected after unwrapping in the wavelet domain. All relevant studies and the corresponding methodological validation are cited in the methods section.

2. I find Table 6 very hard to interpret, and it is arguably the main result of the paper. It should be presented in a graphical way, preferably geographically. This would allow the reader to comprehend the scale of change over the region and study period.

Response: We thank the reviewer for this comment. Figure 10 was included to ease understanding of Table 6 by illustrating the boxplot of each category of land-use changes between 1992-2022, and their corresponding mean and median values. A geographical

representation cannot be done without using 56 subpanels (14 trajectories x 4-time intervals), which resulted too large

3. I think the LULC figures and tables waste a lot of real estate in the paper. I suggest to keep one of them and put the rest into supplementary. Put the InSAR results into the paper, as they are what the authors derive their conclusions from.

Response: We thank the reviewer for the comments. As InSAR is only one of the main "ingredients" of our contribution (which is not specifically focused on monitoring land subsidence using InSAR), we prefer to maintain LULC representation in the main text. However, to follow this reviewer's suggestion at least in part, we have included more information on InSAR such as coherence maps and behavior versus time, Line of Sight (LOS) displacement, and time series in the supplementary materials. Only one time series figure (Figure 6) is put to illustrate land subsidence dynamics across different regions of the study area.

4. Figure 8: please provide a date corresponding to these maps. It would perhaps be more interesting to show how the urbanization has changed over the course of the study period.

Response: We thank the reviewer for this observation. Figure 9 refers to 2020 as provided in the figure caption. We have updated Table 6 by including the time interval of the InSAR analysis into the table. We have equally included annual land use maps of the Douala coastland and urban city for the corresponding land subsidence time interval (2018-2023).

Reviewer 2 Comments

This manuscript regards pioneering work in the subsiding Douala coastland, Cameroon. The authors identified that this area might be subjected to subsidence and subsequently investigated a large portion of it. For this, they used EO techniques; (InSAR and land use change) rather than using local data/information. In data sparse areas this is a reasonable choice. However, the vast scale of the area and the lack of ground truthing data, makes it that certain steps in the analysis requires some elaboration to make the study more sound. Therefore, my main comments are editorial. Mainly it concerns elaboration of i) the physical meaning of linking land us change and subsidence, and ii) which part of the landscape truly covers InSAR observations. Point i is important to give some physical meaning to empirical relations and ii is important because the reader needs to know what is actually subsiding (e.g. truly a vegetated area of a road within a vegetated area). More detailed comments are listed below:

Line 32: I wouldn't state subsidence is a geological phenomenon, it can be, but also hydrological, biological, anthropogenic etc.

Response: We thank the reviewer for their comment. We will update this point and highlight other sources of land subsidence. In line 33, we highlight that land subsidence is caused by changes in the stress regime of the subsurface structure driven by a combination of natural processes and human activities

Lines 35-44: nice global overview. Maybe also implement a South American example? Perhaps the sinking coastal city of Maceio (Brazil), e.g. Vassileva et al. 2021 (Sc. Rep.). Then you also added a ref to mining induced coastal sinking cities

Response: We thank the reviewer for their comment. We have included the ground subsidence from rock salt mining in Maceió by Mantovani et al., 2024.

https://doi.org/10.1016/j.envc.2024.100983

Line 48: space is missing after 'cities'

Response: We thank the reviewer for this detailed observation. We have updated it in the main paper.

Line 57: mention that the Groningen field is underlying a coastal plain (so causing coastal subsidence). This is not clear now.

Response: We thank the reviewer for their comment. In line 57, we use the Groningen gas field as an example of an area subjected to land subsidence partly due to hydrocarbon extraction, because the beginning of land subsidence and the extraction period correlate (Thienen-Visser and Fokker, 2017)

Line 83: so, it’s an estuary within a river branch of the delta system?

Response: We thank the reviewer for their comment. The Douala coastland is an estuarine coastland within the Wouri River delta system, characterised by tidal channels, mangroves, and mixed saline–freshwater conditions.

Fig 1: the blue lines of the river network are not well visible, maybe you can make them dark blue? Like in Fig 4

Response: We thank the reviewer for their comment. We will update it in the main paper.

Section 3.3: I expect some sort of theoretical description that links land use (change) to subsidence derived from InSAR (which part of the land surface produces ps-points, like infrastructure, what are the (physical) mechanisms behind land use change that makes it stand out with respect to VLM - especially when the source of subsidence is at depth, e.g. aquifer systems with their subsidence bowls). Can for example a change from a forest to an agricultural field be recognized in InSAR observations? Or is it all about urbanization? How do you deal with InSAR data sparsity in non-urbanized areas before changing into a city? Please elaborate, not only refer to Minderhoud et al 2018 for this.

Response: We thank the reviewer for this insightful comment. The theoretical link between land-use changes and InSAR-derived subsidence in our study is based on both the physical mechanisms of ground deformation and the spatial distribution of InSAR scatterers (PS/DS points). InSAR primarily detects stable radar targets such as buildings and roads; thus, coherent points are more abundant in urban and industrial zones, while vegetated or agricultural areas exhibit lower coherence. To address data sparsity in non-urbanized zones, we correlated present-day subsidence (2018–2023) with historical land-use transitions (1992–2022), allowing inference of how past changes influence current deformation patterns.

Physically, land-use conversion modifies the subsurface stress regime. Transformations from forest, wetland, or rangeland to built-up areas increase surface loading, reduce infiltration, and promote soil consolidation, particularly in Douala’s soft alluvial deposits. Recently urbanised zones, especially those converted from tree cover or wetland after 2015, exhibited the highest subsidence rates, reflecting ongoing consolidation. In contrast, older built-up zones have stabilised. Transitions such as forest-to-cropland are generally not detectable due to low radar coherence, indicating that InSAR’s sensitivity to land-use change primarily emerges with urbanisation.

Line 203: recent subsidence studies using the GHSL are Cigna et al. 2025 (Sc. Rep.) and Verberne et al. 2025 (Geom. For Eng. and the Env.)

Response: We thank the reviewer for their comment. We will take them into consideration in the main paper.

Section 3.4: So, sentinel-1 starts a decade ago, but your land use data 30 years ago. So how do you relate a land use change in the 1990s to present day subsidence rates for instance? What would be the physical meaning of that? Also, here some elaboration is required explaining the mechanisms behind the empirical relations you are focusing on.

Response: We thank the reviewer for their insightful comment. To clarify, this study does not examine the simultaneous dynamics of land-use change and land subsidence. Rather, our analysis focuses on the relationship between historical (1992–2015) and recent (2017–2022) land-use transitions and the contemporary subsidence rates observed during 2018–2023. We hypothesise that present-day subsidence rates and spatial patterns are, at least in part, influenced by antecedent land-use changes, as summarised in Table 6.

For instance, the conversion of forested areas into built-up zones through urban expansion introduces additional structural loads that can initiate or accelerate soil consolidation processes. The nature and progression of consolidation depend on both the underlying soil properties and the elapsed time between the onset of construction and the period of subsidence measurement. Consequently, variations in subsidence rates between locations may reflect differences in the timing and duration of consolidation following land-use conversion. In Douala, this pattern is evident, as relatively higher subsidence rates are observed in recently developed areas compared to those that were urbanised earlier.

Line 263: space is missing after (B)

Response: We thank the reviewer for this detailed observation. We have updated it in the main paper.

Line 305: why do you consider building elevation to be important? I think it is as well, as it can for instance reflect foundation depth (tall and heavy building have deeper and more stiff foundation for instance, subsiding less). But it could also be that they have shallow foundations and tall buildings sink faster into the coastal sequence – anyway, pls add a sentence why you mention this (Edit: I now read it in line 425, maybe that is too late in the paper).

Response: We thank the reviewer for their thoughtful comment. In this study, building elevation is considered one of the key urban morphological characteristics and is utilised to analyse the land subsidence process. We hypothesise that in sandy lowland areas with low bearing capacity, such as Douala, building height is correlated with foundation depth, taller buildings typically require deeper foundations to compensate for the weak subsurface conditions. Consequently, the observed relationship between building height and land subsidence rates can provide indirect insights into the dominant subsidence mechanism, indicating whether the process is primarily shallow or deep in nature.

Line 336: vegetated areas or infrastructure within vegetated areas? Bc of the location of the InSAR points

Response: We thank the reviewer for their valuable comment. In line 336 (currently line 372), our reference to “vegetated areas” pertains specifically to vegetated zones within

the urban extent of Douala. The analysis here focuses on the Douala metropolitan area, which exhibits a highly heterogeneous landscape comprising built-up areas, vegetated zones, roads, wetlands, industrial sites, and other land-cover types.

Line 338: I don’t think sediment accumulation in waterlogged environments is observable with InSAR. In the coastal plain of the Netherlands and Louisiana uplift is locally also due to updoming of deep salt deposits. Do you have info on deep subsurface processes as well?

Response: We thank the reviewer for their comment. Unfortunately, very little information is available about deep subsurface processes in Douala.

Line 414: typo th

Response: We thank the reviewer for this detailed observation. We have updated it in the main paper.